

## The Extreme Sky - Seven Years of INTEGRAL

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Seven years of successful observations of the sky have been completed within the INTEGRAL mission, in the transition regime between X-rays and  $\gamma$ -rays from  $\sim 10$ -8000 keV. Initially-agreed mission goals have been pursued, and both high-resolution images of point sources and high-resolution spectra of nuclear lines have been obtained. New discoveries have been made, such as X-ray emission from embedded binaries, hard emission tails from AXPs and  $^{60}\text{Fe}$  radioactivity lines; these stimulated both theoretical and observational studies, and now make INTEGRAL a valuable asset for the astronomical survey of high-energy sources across the sky. This contribution summarizes the situation after seven years of the mission, and concludes the 7-year anniversary workshop *The extreme sky* held in Otranto, Italy, in Oct 2009.

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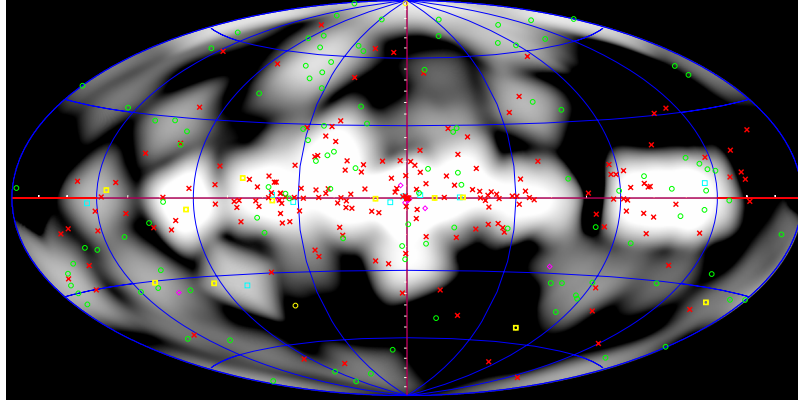
## 1. INTEGRAL's Origins and Expectations

When the INTEGRAL mission was first discussed among scientists, the NASA Compton Gamma-Ray Observatory (CGRO) had just been launched in April 1991 [11], beginning its survey of the  $\gamma$ -ray sky. Developments had led to a change of original plans for CGRO: the fifth originally-planned instrument, a  $\gamma$ -ray spectroscopy experiment (GRSE), had been abandoned for cost and complexity reasons [10]. The Compton Observatory performed its all-sky survey for  $\gamma$ -ray sources in the 100 keV to few GeV range with degree-sized angular resolution and 10-% sized spectral resolution during a 9-year mission. Simultaneously, and specifically during 1994, proposals were prepared for a next advance in this field, aiming at imaging and spectral resolution improvements by an order of magnitude for this energy range: a coded-mask imaging instrument, and a Ge-detector based spectrometer; the *INTEGRAL* mission was given shape [46]. The SIGMA instrument [43] on the GRANAT mission had shown the usefulness of a coded mask for such purpose [27], and that same concept was optimized for INTEGRAL's *Imager* [49, 50]. Ge spectrometers had successfully been applied to observations of  $\gamma$ -ray lines following the spectacular supernova SN1987A in the Large Magellanic Cloud [47], which led the way to high-resolution  $\gamma$ -ray spectroscopy. The science community welcomed these European efforts for a high-resolution spectrometer, and the US Nuclear-Astrophysics Explorer mission concept (NAE) [32] eventually merged with European ideas to form INTEGRAL's *Spectrometer* [28, 51, 52].

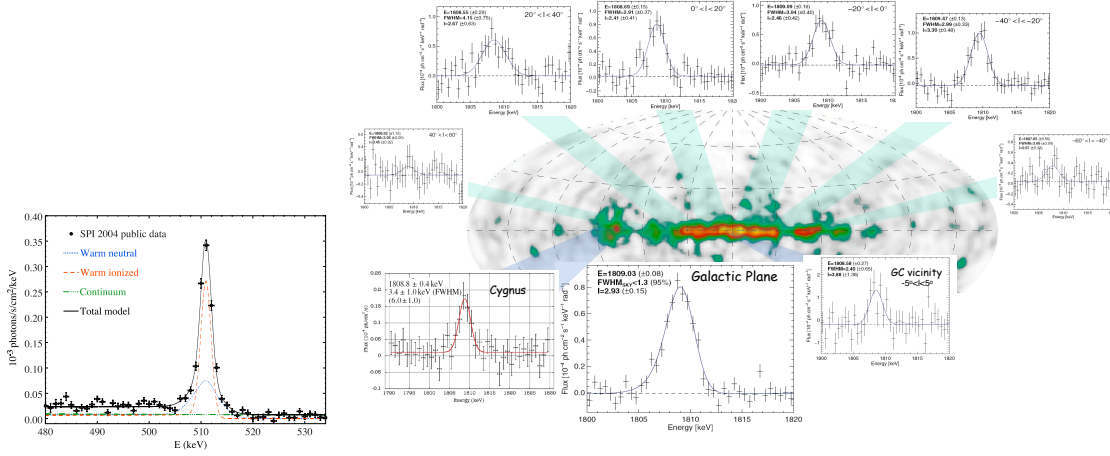
INTEGRAL's mission goals were stated as “... *spectral  $\gamma$ -ray features to be uniquely identified and line profiles to be measured for physical studies of the source region, .... and accurate location and hence identification of the  $\gamma$ -ray emitting objects with counterparts at other wavelengths*” [60] through “...*fine spectroscopy with imaging and accurate positioning*” [60]. The objects then listed as astrophysical targets were *nucleosynthesis, nova and supernova explosions, the interstellar medium, cosmic-ray interactions and sources, neutron stars, black holes,  $\gamma$ -ray bursts, active galactic nuclei, and the cosmic  $\gamma$ -ray background* [60]. Expectations were great, the *quantum leap* for  $\gamma$ -ray astronomy after the Compton Observatory survey was announced widely. Seven years of successful operations are behind us, and hopefully many more to come. The instruments are all in fine shape and performance in spite of some minor defects, and the healthy spacecraft still has fuel for many more mission years [59].

## 2. Scientific Delivery

The first mission years saw impressive statements of scientific delivery – the variety of papers of this conference reflect latest insights and status summaries. We now have in hand the 4<sup>th</sup> IBIS catalogue of sources [1], which shows a total of almost 700 clearly-significant ( $\sim 5\sigma$ ) sources in the 17–100 keV range of hard X-rays. With its source location capability of better than 1 arcmin, comparisons to data at other wavelengths helped to identify the nature of the  $\gamma$ -ray object in 71% of cases, to tell us about their thermal versus non-thermal emission. The  $\gamma$ -ray line spectroscopy measurements with SPI have obtained clearly-resolved line shape measurements for the strongest  $\gamma$ -ray line in the sky, the annihilation line of positrons at 511 keV [17, 3], and  $^{26}\text{Al}$  line spectra resolved for different source regions along the plane of the Galaxy [5, 56]. Line shapes and locations have been interpreted in terms of astrophysical processes of nucleosynthesis sources and



**Figure 1:** The IBIS source catalogue of over 700 sources demonstrates the richness of the sky in  $\gamma$ -ray sources [1]. The fine source location capability of  $1'$  or better has helped to identify the majority of these sources (71%) with known objects, comparing to observations at other wavelengths.



**Figure 2:** The SPI  $\gamma$ -ray spectrometer resolves astrophysical  $\gamma$ -ray lines. *Left:* Positron annihilation  $\gamma$ -rays shape the line at 511 keV, as annihilation occurs in cold neutral, warm and partially-ionized, or hot plasma, with expected line widths increasing in that order. (from [16]). *Right:*  $^{26}\text{Al}$   $\gamma$ -rays have now been seen from different regions along the plane of the Galaxy, and allow to constrain the recent nucleosynthetic history for different massive-star groups in our Galaxy. (from [56]).

interstellar-medium parameters. This clearly demonstrated the *delivery* from both of INTEGRAL's main instruments, the Imager and the Spectrometer, keeping up with the *promises* as cited above.

### 3. Some Hard Lessons

We had to learn that some things are not as easy as hoped for. SPI's instrumental background turned out to be a big challenge, the hope for efficient rejection through the pulse-shape discrimination system was not fulfilled [44]. As a result, sensitivity remains below simulated performances. Nuclear de-excitation lines from the interstellar medium ( $^{12}\text{C}$  and  $^{16}\text{O}$  at 4434 and 6129 keV, respectively) could not (yet) be detected. Detections of less-bright emissions in annihilation  $\gamma$ -rays, in  $^{26}\text{Al}$ , and the discovery of  $^{60}\text{Fe}$   $\gamma$ -rays [55] had to await accumulation of data from five or more

mission years. This is beyond the originally-planned duration of even the *extended* mission; but evaluation committees recognized the issues of properly estimating such a dominating and time-variable instrumental background, and generously supported deviations from the original mission plans. The time variations of the spectral response, incurred from detector degradation resulting from cosmic-ray bombardment, and rectified periodically through *annealings*, lead to additional efforts in maintaining the spectroscopic precision as required for  $\gamma$ -ray line shape analyses.

Gamma-ray lines from supernovae remain a matter of (bad) luck: No sufficiently-nearby ( $<5$  Mpc) supernova of type Ia occurred since INTEGRAL's launch, challenging statistical expectations [15]. The Galactic Cas A supernova remnant's  $^{44}\text{Ti}$   $\gamma$ -rays at 68 and 78 keV were seen with the IBIS instrument and thus confirmed earlier measurements [39]; but SPI's spectrometer fails to obtain a new measurement of the high-energy line from  $^{44}\text{Ti}$  decay at 1157 keV. Although disappointing at first glance, this can be understood from Doppler-broadening of still-fastly-moving ejecta, causing a broader line to drown in SPI's instrumental background [30]. But the hopes for measuring (and interpreting) the  $^{44}\text{Ti}$  line shape from young supernova remnants could not be fulfilled. Similarly, also INTEGRAL does not detect more of the supernovae that are expected from the Galaxy's current rate of core-collapse supernovae, and only confirms earlier constraints from COMPTEL; no new Cas A-like study objects are found [40].

Also the *Imager* instrument encountered difficulties: its spectral response shows a *snake-like* nonlinearity which is difficult to control, signal rise-time differences over the large dynamic range of signal amplitudes for the  $>32000$  imaging-detector pixels present a major challenge [22]. Moreover, seemingly-minor imprecisions in glue applications on the tungsten coded mask holding structure now have been found to limit systematics from artifact features, creeping into images as exposure gets as deep as 70 Ms and beyond. Re- and deepening calibrations are arranged by the instrument and ESA teams, to address these issues within the constraints of the mission.

#### 4. Scientific Surprises and New Challenges

In spite of these difficulties, INTEGRAL data also presented a number of surprises and new discoveries from the  $\gamma$ -ray sky:

New and unexpected sources were detected in the Galaxy, and identified as sources deeply embedded in surrounding molecular clouds [53, 54, 2]. Their intense high-energy emission came as a surprise. Understanding such emission presents a novel challenge. On the other hand, INTEGRAL is able to constrain the contributions from such sources with (non-thermal emission) high-energy tails to the high-energy emission from galaxy clusters, as shown in the Coma cluster [24, 41].

Binaries with  $\gamma$ -ray emission resulting from the interaction of a massive-star's intense wind with the orbiting compact companion star were discovered [19, 13]. Interestingly,  $\gamma$ -ray emission was detected from binary sources seen also in TeV high-energy  $\gamma$ -rays [25, 13], and led to new studies of cosmic-ray acceleration [48, 31].

Gamma-ray emission from highly-magnetized neutron stars were discovered, and helped to classify the *anomalous* X-ray pulsars [20]. Understanding the magnetosphere as the now-plausible source of high-energy emission remains a challenge, and INTEGRAL data extending well beyond 100 keV in energy are crucial in such study [4].

The *transient*  $\gamma$ -ray sky also led to surprises [21, 36]. Magnetar flares such as the INTEGRAL-discovered SGR1806-20 event in 2004 [35, 9, 12] are one example. Other examples arose from  $\gamma$ -ray burst opportunities [34]. For GRBs within INTEGRAL's instrument field of views, which occur at a rate of one a month, a few GRBs were seen with *harder* spectra than expected from the internal-shock synchrotron model, indicating that the GRB engine is not yet understood. Other GRBs, on the contrary, exhibit spectra which are unusually *soft*, and helped to explore the transition range to the phenomena of *X-ray flashes*. Moreover, the anticoincidence system (ACS) of SPI turned out to be useful in GRB studies [14], adding an important GRB monitor with nearly all-sky sensitivity to the interplanetary network, and thus helping GRB locations.

The inner region of our Galaxy is rich in transient sources, presumably mostly accreting X-ray binaries. INTEGRAL's monitoring program [21] identified and tracked many new such binaries. With now a considerable statistical sample, the spatial and luminosity distributions of these transient sources are being studied [23, 29, 37]. It has been recognized that the type of source changes as one steps up into INTEGRAL's  $\gamma$ -ray domain, with cataclysmic variables and coronally-active stars dominating the X-ray domain up to several tens of keV, and low-mass X-ray binaries (LMXB) dominating above [42]. The sample of high-mass X-ray binaries could be substantially increased from INTEGRAL's observation of the hard X-ray regime, and now holds nearly hundred objects; prospects for determining their Galactic distribution are realistic now [23]. Within this sample, more sources with unexpected properties are found, such as neutron-star companions with unexpectedly-low rotation periods, or with surprisingly-intense stellar winds [8].

Among these HMXBs, a new source class emerged, called *superfast X-ray transients* [38, 45]. In these, the wind interaction with the orbiting compact neutron star apparently sets conditions for intense flaring activity of typically  $\sim$ hour durations. Constraining the nature of such outbursts with detailed observations of the temporal and spectral changes promises to provide new and unexpected insights into the phenomena and process of accretion of matter onto a compact neutron star, and the nature of the companion star.

Active galaxies were confirmed to mostly drop sharply in their intensities as one reaches beyond X-ray energies of several keV, as a dusty torus around the active nucleus is believed to absorb radiation. But probing rare active galaxies on the high side of the distribution of absorbing-torus column densities, much fewer such sources were found than had been extrapolated from X-ray observations and theories [26]. As a result, the diffuse cosmic X-ray background with its emission maximum at 30–40 keV cannot be inferred by extrapolation of X-ray emission properties, and such extrapolation explains only  $\sim 10\%$  of the peak emission.

The emission from positron annihilations in interstellar space has been mapped across the sky, and consolidated earlier hints for the bulge region of the Galaxy being by far the brightest emission region on the sky [18, 57, 58]. These maps revealed a surprisingly-symmetric bulge emission, and barely were able to detect annihilation emission from the Galaxy's disk, where most of the candidate sources are located (see [7] for a review, and Churazov et al., this volume).

The  $^{26}\text{Al}$  line could be seen to vary in centroid position, as would be expected from the Galaxy's large-scale rotation [5]. But such variation of line position is small at tenths of a keV, and it was surprising that INTEGRAL's spectrometer turned out to be able to measure interstellar-medium velocities down to the  $100 \text{ km s}^{-1}$  range. This is helped by INTEGRAL's finding that the intrinsic Doppler broadening from ISM kinematics is not as broad as reported before, and instead

rather narrow and below instrumental line widths [6]. Additionally,  $^{60}\text{Fe}$  radioactivity was first clearly measured by INTEGRAL's Spectrometer [55].

## 5. Prospects for INTEGRAL in its Late Years

The INTEGRAL mission is now part of a fleet of astronomy space missions. Coming of age, one may wonder how valuable continued observations with INTEGRAL would be. It is useful to consider the special strengths of this mission for new astrophysical insights.

INTEGRAL's spectrometer SPI features spectral resolution of  $\sim 600 (\frac{E}{\delta E})$ . This capability will remain unrivaled and unique for many years to come: Since many astrophysical lines will be kinematically broadened, specifically from the target objects of supernova explosions (see Cas A's experience, as discussed above), the future instrumental developments targeting  $\gamma$ -ray line studies from supernovae will not need such high resolution. Experiments thus can be optimized towards large collecting areas with less-costly detectors such as CdZn, with adequate spectral resolution for that purpose.

INTEGRAL targets radiation originating in atomic nuclei from cosmic objects. It is likely that observations in this energy regime have only revealed the tip of the iceberg of cosmic sources, even within our Galaxy. It is worth reminding that most astronomical observations from radio through IR, optical, UV and X-ray bands address emission processes of thermal origins, and spectral information arises from line transitions in the atomic shells. This implies that the state of the atomic shell is part of the emission process, or, stated otherwise, this state must be determined for a proper interpretation of the observed emission. Nuclear emission processes, on the other hand, are often rather independent of the thermodynamic parameters of the emission region, such as in lines originating in radioactive decay, or in high-energy collisions from cosmic rays. This window is uniquely addressed by INTEGRAL and its large field-of-view instruments. With luck, nuclear explosions sufficiently nearby may show the usefulness of such observations of radiation of primarily-nuclear origins.

Polarization of light encodes processes of magnetic-field origins in the cosmic source of radiation. For high-energy radiation, the differential Compton scattering process shows angular patterns which encode polarization, and becomes observable at  $\gamma$ -ray energies with a sufficiently-large camera. First results obtained with INTEGRAL on a  $\gamma$ -ray burst and on the Crab pulsar emission are promising [33]. Future observations may further exploit this unique potential.

The INTEGRAL sky survey has emphasized exposure along the plane of the Galaxy. As a result, now deep exposure has been accumulated over regions of the sky which are not as easily accessible by low-orbit missions such as SWIFT. This allows complementarity of sky surveys for active galaxies at high energies (see Krivonos et al., this volume), which can address the issue of which sources are responsible for the cosmic X-ray background in its peak region and above.

Science issues which appear interesting and hot and can be addressed by future INTEGRAL observations are, for example:

- What is the Galactic population of high-energy emitting accreting binaries?
- How does the accretion process occur in close or interacting binaries?
- What is the nature of high-energy emission in high-field magnetospheres near neutron stars?
- What does the morphology of positron annihilation emission teach us about positron sources,



what about positron escape and interstellar propagation?

- What are the state and conditions of hot interstellar medium around massive-star groups?
- How can models of massive-star and supernova structure be aligned with nucleosynthesis of  $^{26}\text{Al}$  and  $^{60}\text{Fe}$  from those objects?
- Which active galaxies and their subtypes are responsible for accumulating to the observed diffuse X-ray background?
- Is emission from  $\gamma$ -ray bursts, or from  $\gamma$ -ray pulsars, polarized?

The way an *observatory* such as INTEGRAL is managed, some tension arises typically in later mission years from the fact that *additional* observations suggested in competitive proposals only add *incremental* data to a large and growing database. Therefore, *new* insights are not expected, at least from persistent sources of high-energy emission. This appears to argue for an observing program being widely-open for targets of opportunity and tracking of source variabilities, in particular favored by INTEGRAL's large field of view which allow some *amalgamation* and *serendipidity*. On the other hand, the unique strengths of INTEGRAL should be utilized to build and consolidate the legacy of results specific to this type of instrumentation, so that astrophysical and deep analysis of these findings (but also future mission proposals to take up and deepen such studies) can be supported with best-achievable precision.

INTEGRAL is now managed by a *Users Group* composed of instrument experts and a broad spectrum of scientists involved in high-energy astrophysics (see also [59]). This group is very effective in discussing the different aspects of observing program alternatives. It turns out a very useful moderator to the diversity of proposed satellite pointings through the annual observing opportunities. Considering the limited gain of such individual and necessarily short (by comparison with existing) exposures, a *Key Program* concept has successfully been implemented. Here, two classes of proposal opportunities were installed: *Long Key Program* observations set the general program of where INTEGRAL's survey of the  $\gamma$ -ray sky will be directed to, and a second category of proposals requests *data rights* from such prior-selected pointings for analysis of specific astrophysical questions or sources. In a *Gedanken-Experiment*, this author also presented a more extreme version of this concept, where exposures are directed by the key program and user group such that synergies are maximized. [One scenario would be to point INTEGRAL at intermediate latitudes along the plane of the Galaxy. This could complete and complement the Galactic-plane survey with the brightest plane regions being in outer field-of-view regions. Simultaneously, exposure would be added to constrain latitudinal extents of diffuse high-energy emission of special interest, such as positron annihilation emission. Active Galaxies could be surveyed at those intermediate latitudes, deepening existing exposures sufficiently for meaningful constraints.] It will remain a challenge to ensure community interest in INTEGRAL observations, especially if the common scheme of regular and frequent *observation opportunities* would be deviated from. But a fresh look at the options best-suitable for INTEGRAL could be worthwhile. In any case, INTEGRAL's next seven years could be fruitful to harvest and consolidate the excitements of the extreme universe from its high-energy emission.

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It was a pleasure to celebrate seven years of INTEGRAL in Otranto!

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